Opto-Electronic Carrier-Envelope-Phase Detection

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Abstract: The possibility of detecting the carrier-envelope (CE-) phase by measuring directly the inversion in a two-level medium after excitation with an off-resonant few-cycle laser pulse is demonstrated by numerical simulations.

With the arrival of laser pulses consisting of only few optical cycles, attention has been drawn to effects which not only depend on the electric field envelope, but also on the phase between the rapidly oscillating carrier wave and the envelope. Different approaches have been used for detecting this carrier-envelope (CE-) phase φ_{CE}. Recently, it has been shown that a promising candidate is carrier-wave Rabi flopping [1]. Carrier-wave Rabi flopping is defined as the regime in which a resonant excitation of a two-level system is so strong, that significant inversion is generated during one optical cycle [2]. This regime occurs when the Rabi frequency approaches the carrier frequency. It has been demonstrated that the corresponding Mollow sideband radiation emitted from the two-level system at different harmonics can interfere with each other or with the bulk or surface generated second harmonic radiation, producing a CE-phase sensitive photocurrent in a detector [3]. In this paper, we show that off-resonant excitation of a two-level system, i.e., in the weak-field limit there is no excitation of the system at all, may lead to a phase sensitive inversion after passage of the pulse in the strong field limit. The phase sensitive inversion can be directly probed optically or it can be read out electronically by an applied field, resulting in a compact electronic phase detector. A portion of the detector current is directly proportional to the carrier-envelope phase.

We consider sinc-shaped pulses, which are a fairly good description of recently generated few-cycle laser pulses [4]. They are characterized by their full-width at half-maximum pulse duration T_{FWHM}, their carrier frequency f_0 and their maximum field strength E_{max} occurring at the center of the pulse for vanishing CE-phase. These pulses have a rectangular spectrum, extending from f_0-$\Delta/2$ to $f_0+\Delta/2$ with $\Delta=0.886/T_{FWHM}$. The two-level medium is characterized by its resonance frequency $\omega_{ab}=(E_a-E_b)$/hbar, and its dipole matrix element d. Relaxation processes are considered by the phase relaxation time T_2; the energy relaxation processes can be neglected for the time scales considered.

The dynamics of the two-level system is found by numerically solving the Bloch equations.

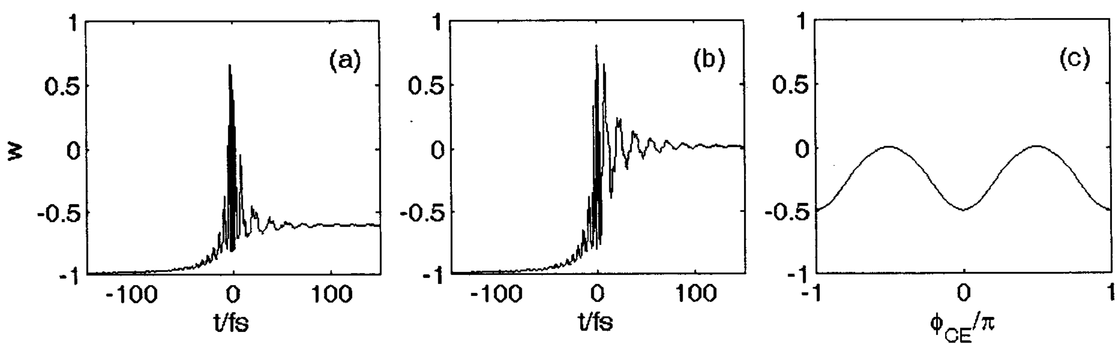

Fig. 1: Inversion w for a two-level atom interacting with a 5 fs optical pulse: (a) time evolution for $\varphi_{CE}=0$, (b) time evolution for $\varphi_{CE}=-\pi/2$, (c) phase dependence of the remaining inversion.

As an example, we compute the inversion for a 5 fs pulse with a maximum field strength of E_{max}=6 V/nm and a carrier frequency of f_0=375 THz (λ_0=800 nm). The resonance frequency of the two-level system is chosen as ω_{ab}=3.28/fs, corresponding to the band gap of AlAs, and for the dipole matrix element we assume d=0.4e nm. The phase relaxation time used in the simulations is T_2=40 fs. Fig. 1 shows the inversion w. Strong oscillations of w occur while the system interacts with the pulse, and after the decay of the pulse, w approaches a constant value. The remaining inversion is w_0=-0.61 for φ_{CE}=0 and $w_{-\pi/2}$=0.01 for φ_{CE}=-π/2. Fig. 1(c) shows that the inversion remaining in the system is modulated with twice the CE-frequency since the Bloch equations are invariant with respect to simultaneous inversion of the electric field and the dipole moment, leaving the inversion invariant.

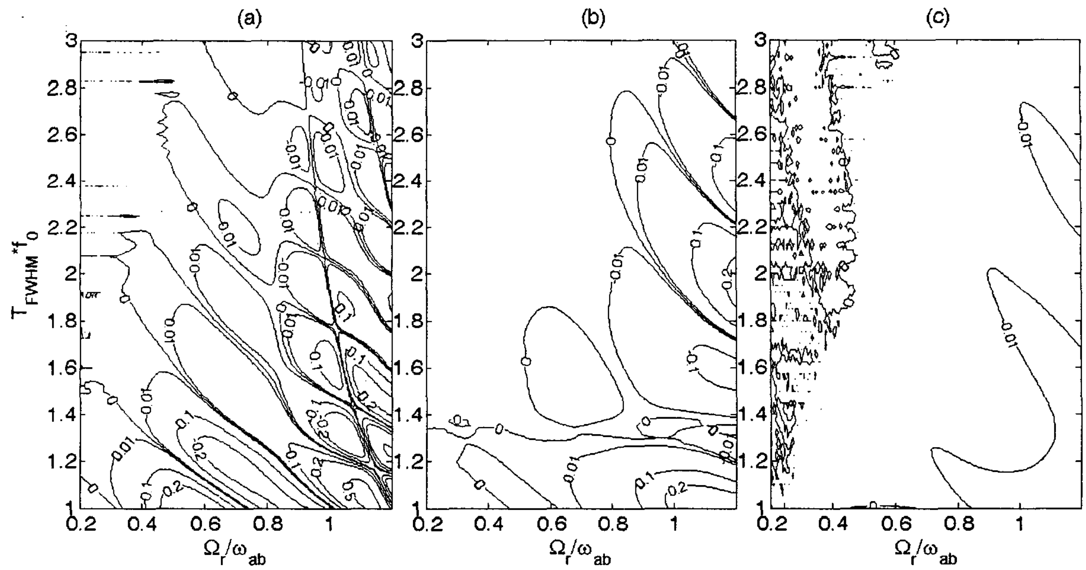

Fig. 2: CE-phase sensitivity of the inversion: (a) f_0/f_{ab}=0.5, (b) f_0/f_{ab} =0.75, (c) f_0/f_{ab}=1.

Fig. 2 shows the fringe visibility of the CE-phase in the inversion after passage of the pulse, which is defined as $w_{rel}=(w_0-w_{-\pi/2})/(w_0+w_{-\pi/2}+2)$ for various carrier frequencies f_0 as a function of the pulse duration in terms of optical cycles, f_0T_{FWHM}, and Rabi frequency Ω_r=dE_{max}/hbar. The phase relaxation time is set to T_2f_{ab}=20. A value of w_{rel}=±1 indicates maximum possible modulation of the inversion, w_{rel}=0 indicates no modulation. High sensitivity of the inversion with respect to the CE-phase is found for large values of the maximum electric field, where the Rabi frequency is a considerable fraction of the carrier frequency. Regions with positive and negative relative inversion alternate, separated by contour lines with w_{rel}=0. For f_0/f_{ab}=0.5, the pulse spectrum is completely off resonance from the transition of the two-level atom for all pulse durations considered, and thus no linear absorption occurs. If f_0/f_{ab} =0.75, the spectrum overlaps with the transition only for pulses shorter than about 1.33 optical cycles. Thus, modulation of the inversion with twice the CE-frequency can be observed far off resonance. It turns out that the strongest phase dependence at the lowest electric field occurs for excitation where the carrier frequency is half the transition frequency, i.e., the two-photon transition is resonant, which is a consequence of the structure of the Bloch equations. The phase sensitivity in the inversion does not very strongly depend on the carrier frequency of the pulse, due to the broadband excitation. However, Figure 2(c) clearly shows that off-resonant excitation is by at least one order of magnitude more effective than resonant excitation.

The inversion could be detected optically, either by an additional probe beam or by the short wavelength spectral components of the pulse itself, that is resonant with the two-level system and delayed against the excitation part of the pulse. It is even more appealing to extract the modulated inversion from a diode-like structure in form of an external current. Experimental investigations of these possible novel electronic phase detection schemes are in progress.

References

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